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Unravelling interactions between salt marsh evolution and sedimentary processes in the Wadden Sea (south-eastern North Sea)

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Abstract:

Salt marshes in the Wadden Sea constitute about 20% of all salt marshes along European coasts. They are of immense importance for coastal protection reasons and as habitat for coastal plant, bird, and invertebrate species. The Wadden Sea is a coastal sedimentary ecosystem in the south-eastern North Sea. Besides salt marshes, it is composed of tidal flats, high sands, and sandy shoals, dissected by (sub)tidal channels and located behind barrier islands. Accelerated global sea-level rise (SLR) and changes in storm climate have been identified as possible threats for the persistence of the Wadden Sea ecosystem including its salt marshes. Moreover, it is known that the amount and composition of the sediment available for salt marshes are the most important parameters influencing their ability to adapt to current and future SLR. Assessing these parameters requires a thorough understanding of the sedimentary system of the salt marshes and the adjacent tidal basins. In the present review, we investigate and unravel the interactions of sedimentary processes in the Wadden Sea with the processes taking place on salt marshes. We identify the most crucial processes and interactions influencing the morphological development of salt marshes in the Wadden Sea. A conceptual model is proposed, intended as a framework for improved understanding of salt marsh development and for incorporation into new salt marsh models. The proposed model may also be applicable to regions other than the Wadden Sea.

Review Article

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Salt marshes in the Wadden Sea constitute about 20% of all salt marshes along European coasts. They are of immense importance for coastal protection reasons and as habitat for coastal plant, bird, and invertebrate species. The Wadden Sea is a coastal sedimentary ecosystem in the south-eastern North Sea. Besides salt marshes, it is composed of tidal flats, high sands, and sandy shoals, dissected by (sub)tidal channels and located behind barrier islands. Accelerated global sea-level rise (SLR) and changes in storm climate have been identified as possible threats for the persistence of the Wadden Sea ecosystem including its salt marshes. Moreover, it is known that the amount and composition of the sediment available for salt marshes are the most important parameters influencing their ability to adapt to current and future SLR. Assessing these parameters requires a thorough understanding of the sedimentary system of the salt marshes and the adjacent tidal basins. In the present review, we investigate and unravel the interactions of sedimentary processes in the Wadden Sea with the processes taking place on salt marshes. We identify the most crucial processes and interactions influencing the morphological development of salt marshes in the Wadden Sea. A conceptual model is proposed, intended as a framework for improved understanding of

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I Introduction

The Wadden Sea ecosystem stretches over 450 km along the coast of The Netherlands, Germany, and Denmark and is characterized by a semidiurnal tidal regime (Fig. 1) (CWSS, 2008). It is regarded as one of the world's largest unbroken wetland systems, consisting of barrier islands, sandy shoals, tidal sand and mud flats, (sub)tidal channels, and coastal salt marshes. The salt marshes are located at the interface between the tidal flats and the upland and cover a total area of about 400 km^2. Nearly 50% of them are foreland marshes, in most cases artificially created by the implementation of brushwood groynes in the tidal flats, and located in front of the dikes along the mainland coast (Esselink et al., 2009). In contrast, most natural salt marshes are found at the leeward side of the barrier islands (back-barrier marshes) (Bakker et al., 2005).

Salt marshes in the Wadden Sea are considered important for coastal protection (Möller, 2006; Möller et al., 1999) and as habitat for coastal birds, invertebrates, and specialized plant species

(Niedringhaus et al., 2008; van der Maarel and van der Maarel-Versluys, 1996). In addition, salt marshes have an important filter function with regard to nutrients and pollutants (e.g. heavy metals) (Reise et al., 2010) and act as a sink for fine-grained sediments (Andersen and Pejrup, 2001; Pejrup et al., 1997).

Growth and survival of salt marshes are primarily controlled by hydromorphological parameters such as inundation frequency and sediment availability (Pethick, 1981; van Wijnen and Bakker, 2001) as well as the influence of vegetation on the sedimentation process itself (Fagherazzi et al., 2012). Therefore, salt marshes are highly susceptible to changes of the hydromorphological regime, triggered, for example, by a rising sea level and/or increased storm activity (Morris et al., 2002; Mudd et al., 2004; Reed, 1995). Various modelling studies have shown that salt marshes may be able to accrete with roughly the same rate as sea level rises, if sediment availability is sufficient (French, 1993; D'Alpaos et al., 2011; Kirwan et al., 2010). However, as a consequence of recent climate change (including sea level rise (SLR)) and various anthropogenic pressures, salt marshes have been lost and/or are expected to be lost in the future due to drowning and/or lateral erosion in many parts of the world (Duarte et al., 2008; McFadden et al., 2007; Nicholls et al., 1999). In contrast to this global trend, salt marsh areas in the Wadden Sea have remained stable or have been expanding since the end of embanking about 25 years ago (Esselink et al., 2009; Wolff et al., 2010; Stock, 1998). Partly, this trend is due to the artificial creation of foreland marshes (Esselink et al., 2009). For the 21st century and beyond, accelerated SLR has been identified as a major threat for the salt marshes in the Wadden Sea, since not enough sediment may be available for their vertical growth (e.g.

Andersen et al., 2011; van Wijnen and Bakker, 2001) and since artificial salt marsh creation is reduced for nature protection reasons (Esselink et al., 2009).

For the future ability of the Wadden Sea salt marshes to adapt to SLR, it is assumed that the local availability of fine-grained sediments is the most important variable (Andersen et al., 2011; Schuerch et al., 2013). This implies that understanding the import of fine-grained sediments into the tidal basins as well as the sediment transport processes on the tidal flats and the salt marshes is crucial for estimating the future development of these marshes. However, the interactions between the sedimentary processes of the tidal basins, tidal flats, and salt marshes are insufficiently studied and have not yet been incorporated into predictions for future salt marsh development.

With this review, we aim to identify knowledge gaps regarding the main processes that control morphodynamics within the tidal basin – tidal flat – salt marsh continuum and suggest how these gaps can be bridged in salt marsh modelling. For this purpose we have developed a conceptual model that helps to improve the formulation of salt marsh models that predict the ability of coastal salt marshes to adapt to future SLR. Rather than looking at salt marshes as an isolated landscape feature, a more comprehensive and broader-scale approach is taken for highlighting the role of salt marshes in the surrounding sedimentary system. The Wadden Sea ecosystem, in this context, serves as a case study, since it can be considered representative of many similar coastal systems around the world, and extensive research with respect to its morphological functioning has been conducted (Wang et al., 2012).

II Methodology

In the following sections, we outline the sedimentary processes and interactions relevant for the morphological development of salt marshes in the Wadden Sea. Where possible, existing process knowledge is reviewed based on studies directly referring to the Wadden Sea ecosystem. However, for site-independent processes driving the Wadden Sea sedimentary system, a more general review approach is taken referring to the most important literature in the field.

We start with a synthesis of the processes governing the salt marsh itself and the identification of knowledge gaps. We continue with a description of the existing and missing knowledge on tidal flat dynamics and the processes taking place in the tidal basin. The importance of all these processes for the morphological development of salt marshes in the Wadden Sea is thereby highlighted. In the end, we integrate this knowledge in a conceptual model that will help salt marsh modellers to expand their models and improve the model performance with respect to short- and long-term temporal as well as spatial variations in salt marsh development.

III Morphodynamics of coastal salt marshes

1 Vertical salt marsh development

a Processes of vertical salt marsh growth. Driven by regular tidal to episodic wind induced inundations, the growth of salt marshes is controlled by a continuous input of mainly mineral (and much less organic) sediment brought onto the salt marsh by the flooding water. Such allochthonous accretion is strongly related to the relative elevation of the salt marsh within the tidal frame, the inundation frequency, and the amount of external sediment supplied by the flooding water (Kirwan et al., 2010; French, 1993; van Wijnen and Bakker, 2001). Besides the allochthonous accretion, salt marshes accrete as a result of autochthonous growth, the accumulation of aboveground and belowground biomass including the growth of benthic microflora (e.g. cyanobacteria and eucaryotic algae, such as diatoms and *Vaucheria*) (Chmura, 2013; Sullivan and Currin, 2002).

For allochthonous marsh accretion, vegetation acts as a facilitating ecosystem-engineer. It reduces lateral and vertical marsh erosion and stabilizes the soil through rooting and other modifications of the soil properties (Feagin et al., 2009; Howes et al., 2010). Moreover, the aboveground plant structures reduce flow velocities and turbulence, enhancing the deposition of mineral and organic sediment particles by trapping suspended sediments directly and by increasing particle settling velocities in densely vegetated environments (Fig. 2) (Leonard and Croft, 2006; Mudd et al., 2010; Nepf, 1999; Stumpf, 1983). Spatial variability in the depositional pattern is introduced by the presence of vegetation as suspended sediment concentrations of the flooding water are depleted while travelling over the vegetated marsh surface (Christiansen et al., 2000; French and Spencer, 1993; Temmerman et al., 2003a).

Depending on the marsh elevation, different vegetation types and densities establish on the marsh that vary with respect to their physical plant characteristics (e.g. stem diameter and stiffness, leaf area, vertical biomass distribution) and their potential to reduce flow velocities and turbulences as well as their ability of directly capturing sediments (Neumeier and Amos, 2006; Mudd et al., 2010; Marani et al., 2013). Additionally, sedimentation rates over vegetated marsh surfaces vary spatially depending on the ratio of inundation height to vegetation height (Temmerman et al., 2005) with smaller spatial variability, when the marsh vegetation is completely submerged during an inundation event (Temmerman et al., 2005).

Marsh growth via vertical accretion is counteracted by autocompaction (Allen, 2000). This process is generally assumed to be negligible on allochthonous marshes, but highly important in autochthonous marshes (Cahoon et al., 1995; Allen, 2000). However, Bartholdy et al. (2010) find autocompaction to be of major importance for a barrier-connected mineralogenic salt marsh in the Danish Wadden Sea. Besides autocompaction, the salt marsh surface may also be lowered by external factors, such as tectonic or human-induced soil subsidence (e.g. de Vlas, 2005).

If total marsh accretion exceeds the combined effect of soil subsidence, autocompaction, and eustatic SLR, the marsh elevation increases relative to mean sea level (MSL). Inundation frequency then decreases and sedimentation rates slow down when vegetation succession proceeds from pioneer marsh over low marsh to high marsh vegetation (Adam, 1990; Bockelmann et al., 2002; Leendertse et al., 1997; Olff et al., 1997).

b Vertical salt marsh growth under the influence of SLR. Salt marsh growth usually exists in a quasi dynamic equilibrium with SLR (Allen, 1995; Allen, 2000; Morris et al., 2002). More frequent and higher inundation events enhance mineral sedimentation when sea level rises. A parallel increase of biomass is observed on the salt marsh up to a critical SLR rate (Morris et al., 2002). Given sufficient sediment supply, most marshes are likely to survive SLR (Kirwan and Temmerman, 2009). If sediment supply decreases, the salt marsh may not be able to grow fast enough (Andersen et al., 2011), leading to regressive succession (Warren and Niering, 1993) or drowning of the marsh (Fig. 3) (D'Alpaos et al., 2011; Kirwan et al., 2010). In the Danish Wadden Sea, Andersen et al. (2011) found indications for a decreasing sediment supply, either caused by a long-term regime shift or by short term variations in the sedimentary system of the Wadden Sea. Also in other parts of the Wadden Sea, trends of regressive succession are currently observed (Leendertse et al., 1997; Schröder et al., 2002; Stock, 2011), although this may partly be attributed to grazing activities (Bakker, 1985; Stock, 2011; Nolte et al., 2013). Apart from local sediment supply, the survival of salt marshes is crucially dependent on tidal range (Fig. 3) (Harrison and Bloom, 1977; French, 1993; D'Alpaos et al., 2011; Kirwan et al., 2010). In macro-tidal environments tidal currents are stronger, thereby enhancing sediment resuspension in the tidal basin and on tidal flats in particular, resulting in a higher sediment supply for the salt marsh (Temmerman et al., 2004a). Additionally, a large tidal range increases the ability of salt marshes to cope with SLR by allowing the marsh to cover a wider elevational range, thus surviving longer even if marsh elevation decreases relative to MSL (Kirwan and Guntenspergen, 2010).

c Vertical salt marsh growth and storm activity. Apart from SLR and the prevailing tidal regime the occurrence of strong onshore wind and storm events crucially affects marsh development

(Bartholdy et al., 2004; Schuerch et al., 2013). Positive effects of storm activity on vertical salt marsh accretion rates are increased inundation frequencies and heights as well as increased sediment supply (Stumpf, 1983; Bartholdy et al., 2004; Bellucci et al., 2007; Schuerch et al., 2012). Sedimentation rates are generally assumed to gradually increase with higher inundation depths, since sediment concentrations of the flooding water and the absolute amount of sediment transported onto the marsh platform are higher (Temmerman et al., 2003b). Nevertheless, it appears that largest sedimentation rates are associated with time periods in which many strong wind or weak storm events occur, while the occurrence of extreme storm events seems to be less important (Bartholdy et al., 2004). This may be explained simply by the frequency of inundation events, but also by the high probability of inundations overtopping the vegetation canopy. This is, in turn, associated with higher depth-averaged flow velocities, a process, which has hardly been investigated, but is discussed in more detail later. Consequently, sedimentation rates increase more slowly with increasing inundation height as soon as the vegetation canopy is completely submerged during inundation (Schuerch et al., 2012; Neumeier and Amos, 2006).

Generally, micro-tidal marshes have been shown to benefit more from increased storm activity than macro-tidal marshes, since sediment dynamics in micro-tidal marshes are rather controlled by wind induced processes than in macro-tidal marshes, which are more governed by tidal currents (Stumpf, 1983; Kolker et al., 2009). Additionally, the effect of storm surges with regard to inundation heights and frequencies as well as increased sediment supply tends to be relatively more important in micro-tidal marshes than in macro-tidal marshes (Stumpf, 1983).

2 Lateral marsh dynamics

a Physical drivers for lateral marsh erosion. Besides vertical growth, salt marsh development is subject to lateral marsh dynamics. Lateral salt marsh erosion and expansion are suggested to be part of a cyclic behaviour, where an erosive phase of salt marsh retreat is followed or accompanied by the re-establishment of pioneer vegetation in front of the marsh platform (Yapp et al., 1917; Redfield, 1972; Esselink et al., 2009; van de Koppel et al., 2005; Singh Chauhan, 2009). Salt marshes may emerge at upper tidal flats when and where sediment accretion outpaces SLR with inundation frequency and bottom shear stress gradually decreasing. The developing vegetation stabilizes the sediment and further enhances sediment accretion (Fig. 2) (Orson et al, 1985; van de Koppel et al., 2005). In case sediment supply is not sufficient for the tidal flat to adapt to SLR (e.g. due to decreased sediment availability or increased SLR), the tidal flat in front of the salt marsh is lagging behind the accretion rate on the salt marsh platform (Fagherazzi et al., 2006). A steepening scarp develops at the edge of the salt marsh, prone to wave attacks, and salt marsh retreat by lateral erosion is initiated (Fig. 5) (Mariotti and Fagherazzi, 2010). This process may lead to catastrophic collapse of an entire salt marsh (Mariotti and Fagherazzi, 2013). Callaghan et al. (2010) showed that gently sloping and highly elevated tidal flats with high sediment stability most effectively attenuate wave energy, even at highly exposed sites, and thereby inhibit lateral erosion of salt marshes (Callaghan et al., 2010). Locally, this can also result in a reduced sediment supply for the vertical growth of the salt marsh (Reed, 1988; van Leeuwen, 2008).

Besides the morphology of the tidal flats, wave impacts on seaward marsh edges and on the adjacent tidal flats are influenced by local hydrodynamics. Strong wind or storm events producing waves within tidal basins may coincide with high tide, when the tidal flats are completely inundated. In such a case, larger fetch lengths, wave heights, and wave periods increase the probability of vertical erosion of higher elevated tidal flats (Fagherazzi and Wiberg, 2009). Elevated water levels may also amplify marsh edge erosion, since incoming waves could directly reach to the scarp of the salt marsh (Tonelli et al., 2010).

b Lateral marsh erosion in the Wadden Sea. The process of lateral salt marsh erosion is of great importance in the Wadden Sea. Successive embankments have reduced salt marsh area by about 90% over the last millennium and often have shifted the coastline seaward (Reise, 2005). As a consequence, tidal basins became truncated at the landward side and the loss of area increased the hydrodynamic energy due to an increased tidal range and enhanced storm tide wedge (Wang et al., 1995; Flemming and Nyandwi, 1994; Reise, 2005). Lateral erosion at the seaward edges of the foreland marshes was initiated (Reise et al., 2003). Brushwood groynes were set up on the tidal flats fronting sea walls to attenuate wave energy and to promote sediment accretion (Wolff et al., 2010). On these dike forelands, fast lateral expansion at the expense of mud flats is observed combined with very high vertical accretion rates of up to 18 mm/yr (Stock, 2011).

Meanwhile, the presence of a continuous dike line along most of the mainland coast of the Wadden Sea inhibits the inland migration of the foreland marshes, which would be their natural response to SLR and increased hydrodynamic energy. Wherever the marsh is laterally eroding or vertical accretion rates in the pioneer and low marsh zones are below current SLR rates, the marshes are squeezed in between the sea and the dike. This phenomenon, usually referred to as "coastal squeeze", has been shown to intensify with accelerated sea level rise and stronger storm activity (Bartholomä and Flemming, 2007; Doody, 2004; Flemming and Nyandwi, 1994).

3 Knowledge gaps in understanding of salt marsh dynamics

Having evaluated the available literature related to vertical and lateral salt marsh dynamics, we conclude that the general mechanisms of vertical salt marsh accretion and lateral salt marsh development are well understood and described for homogenous salt marshes with a constant sediment supply. Existing salt marsh models (e.g. Randerson, 1979; Krone, 1987; Allen, 1990; French, 1993; D'Alpaos et al., 2007; D'Alpaos et al., 2011; Kirwan et al., 2010; Marani et al., 2010; Mariotti and Fagherazzi, 2010; Mudd et al., 2004; Fagherazzi et al., 2006) have proven their great potential for gaining process knowledge, since many of the involved processes are hard to measure (Nolte et al., 2013). Most of these models, however, exhibit shortcomings in the representation of spatial sedimentation patterns and with temporally varying environmental boundary conditions (Andersen et al., 2011). As the main reasons for these shortcomings we identify the following knowledge gaps:

1) Bio-physical interactions between the marsh vegetation and the hydromorphological processes relevant for the vertical accretion processes on salt marshes are hardly investigated yet (Temmerman et al., 2005; Neumeier and Amos, 2006; Marani et al., 2013). These processes include the spatial influence of heterogeneous marsh vegetation on particle flocculation, hence particle sizes and net sediment flux affecting vertical accretion rates. Marani et al. (2013) have demonstrated the importance of such spatial heterogeneity for the marsh development and concluded that these may affect the resilience of marshes against sea level rise and sediment depletion.

2) Very little attention has been given to the effect of vegetation height in relation to inundation height on sedimentation rates. While a few authors have compared the hydrodynamic influences of emerging and submerged marsh vegetation (Temmerman et al., 2005; Neumeier and Amos, 2006), nothing is known on how this ratio quantitatively influences long-term sedimentation rates. Assuming a significant increase of depth-averaged flow velocities once the marsh vegetation is completely submerged, one may expect a decrease of depth-averaged settling velocities. This would be associated with lower sedimentation rates than if a constant settling velocity is assumed. Specifically, this effect may be important if changes in the tidal range and/or changes in storm patterns in combination with SLR result in greater inundation depths.

3) Even though, it is well understood that the morphological development of salt marshes primarily depends on local sediment supply, a thorough understanding of how the temporal variability of this parameter affects the short-term and long-term development of coastal salt marshes is not available (Andersen et al., 2011). Such temporal variations could be induced by increased hydrodynamic energy, e.g. as a consequence of an increased tidal range or a phase of stronger storm activity, or by changes in the sediment dynamics of the surrounding coastal environment, such as the sediment resuspension from tidal flats or the import of sediment into the tidal basin. A range of conceptual numerical models is employed to investigate these processes and their impacts on the lateral marsh development and the local sediment supply of salt marshes (Marani et al., 2010; Mariotti and Fagherazzi, 2010; Tonelli et al., 2010). However, none of these models has considered the large temporal variability in the stability of tidal flat sediments.

A better understanding of these sedimentary processes could improve the reliability of predictions for future salt marsh development and would help to evaluate whether observed trends are a result of a long-term regime shift (e.g. triggered by SLR) or whether they are induced by short-term variations in storm activity, for example (Schuerch et al., 2013; Andersen et al., 2011).

IV Sediment dynamics on the tidal flats and in the tidal basins

1 Sediment resuspension on tidal flats

Sediment resuspension on tidal flats positively influences vertical accretion rates on salt marshes through increased sediment availability (Callaghan et al., 2010). At the same time, lateral erosion may be caused as a consequence of vertically eroding tidal flats and hence decreasing wave attenuation in front of the salt marsh (Mariotti and Fagherazzi, 2010). Sediment resuspension on tidal flats is a function of the erodibility of the sediment and the prevailing shear stress (Mariotti and Fagherazzi, 2010). The process of sediment resuspension starts when the prevailing shear stress induced by tide- or wind-driven currents as well as (breaking) waves exceeds the critical shear stress of the sediment surface (Miller et al., 1977; van Rijn, 1993; Andersen et al., 2007; Mariotti and Fagherazzi, 2010). In most locations the wind wave-induced shear stress is the dominant term for erosion on tidal flats (Le Hir et al., 2000; French et al., 2000). The erosion rate thereby depends on the change of the critical shear stress within the sediment surface layer (Sanford and Maa, 2001).

a Physical parameters affecting sediment stability. The erodibility of sediments is directly related to its grain size composition (Hjulström, 1955). For non-cohesive (sandy) sediments the critical shear stress continuously increases with higher grain sizes (Soulsby and Whitehouse, 1997). For cohesive (muddy) sediments it increases with smaller particle sizes (Hjulström, 1955) and stronger consolidation (Postma, 1961).

In natural environments, sediments are mostly a mixture of non-cohesive sandy and cohesive muddy material (Andersen et al., 2010). Depending on the mineralogy and grain size composition of the sediment, the highest critical shear stress is found at mud contents of about 30-50% (Le Hir et al., 2007; Mitchener and Torfs, 1996; Grabowski et al., 2011). Based on laboratory experiments (Panagiotopoulos et al., 1997), Ahmad et al. (2011) show that the critical shear stress moderately increases with higher mud contents up to a mud content of about 50%.; above 70% it dramatically decreases. Similarly, Panagiotopoulos et al., (1997) suggests a maximum critical stress at a mud content of 50%.

b Grain size distribution in the tidal basins of the Wadden Sea. As a consequence of land reclamation and "coastal squeeze", the finest grain size fraction in vicinity of the mainland has been depleted in comparison to pre-embankment conditions (Flemming and Bartholomä, 1997; Flemming and Nyandwi, 1994; Mai and Bartholomä, 2000). This depletion is intensified in narrow tidal basins and is assumed to continue as a consequence of increased SLR and storm activity (Bartholomä and Flemming, 2007; Flemming and Nyandwi, 1994; Mai and Bartholomä, 2000). Under storm conditions, wave-induced resuspension of tidal flat sediments and the following export of primarily fine-grained material (Bartholomä and Flemming, 2007; Lettmann et al., 2009) as well as an increasing amount of coarse-grained sediments imported into the tidal basin via suspended load transport are responsible for this trend (Lettmann et al., 2009; Santamarina Cuneo and Flemming, 2000).

A continuing depletion of fine-grained sediments could lead to higher sediment instability on the tidal flats with less than 30% fine-grained sediments at present, and to higher sediment stability on tidal flats with currently more than 50% fine-grained sediments (Le Hir et al., 2007; Mitchener and Torfs, 1996; Grabowski et al., 2011). Hence, it could affect the availability of fine-grained sediments for the salt marshes.

c Biological parameters influencing sediment stability. The biotic activity in and on the sediment is considered as a major factor mediating the mud content of the sediment via deposition of micro-phytoplankton, production of micro-phytobenthos as well as pelletisation of macro-zoobenthos (Andersen et al., 2010). Even more importantly, biological activity is directly affecting the stability of the sediment (Reise, 2002).

Among the biological parameters influencing the stability of tidal flat sediments, particular emphasis is given to the influence of benthic diatoms and cyanobacteria. In the Wadden Sea, these have been shown to increase the sediment stability by the production of extracellular polymeric substances (EPS) as well as colloidal carbohydrates and enhance local sedimentation by direct trapping of suspended sediment (e.g. Andersen et al., 2010; Austen et al., 1999; Lanuru et al., 2007; Paterson, 1989; Stal, 2010). The biomass of diatoms is restricted by the availability of light and nutrients as well as by grazing and resuspension through the macrozoobenthos. Highest concentrations are usually found in April and September (Andersen et al., 2010) and on higher elevated tidal flats (Austen et al., 1999). It should, however, be noted that benthic diatoms, occurring on the sediment surface only influence the critical shear stress at the sediment surface, while they do not decrease the erosion rate, once the critical shear stress has been exceeded (Andersen, 2001; Mariotti and Fagherazzi, 2010).

Another important biological influence on the erodibility of the tidal flats is the presence of macrozoobenthos, either stabilizing or destabilizing the sediment surface (Knaapen et al., 2003; Volkenborn et al., 2007). In the Wadden Sea, the lugworm (*Arenicola marina*), for example, as one of the most prevalent macrobenthic animals, has been shown to increase the erodibility of the sediment by intense bioturbation. This activity also inhibits the colonization of potentially sediment-stabilizing species, such as the tube-building polychaetes *Polydora cornuta* and *Lanice conchilega* (Lanuru, 2004; Volkenborn et al., 2009). In any case, benthic macrofauna tends to increase the surface roughness therefore enhancing the erodibility of the sediment (Lanuru, 2004). Some benthic macrofauna species, such as the mud snail *Hydrobia ulvae* additionally increase the erodibility of the sediment indirectly by grazing the biofilms of diatoms and producing fecal pellets that are easily erodible (Andersen, 2001; Andersen and Pejrup, 2002).

2 Flocculation processes and floc settling velocity

The settling velocity of suspended sediment is generally considered as a key factor for the sediment dynamics in an estuary or coastal lagoon (Mantovanelli, 2005; van Leussen, 1988; Winterwerp, 2002). While in theory, the settling velocity of non-cohesive single particles is shown to be a function of particle size only (Soulsby and Whitehouse, 1997), in reality it is controlled by the aggregation of cohesive sediment particles into flocs (Krone, 1962). Changes of sediment composition and suspended sediment concentrations affect flocculation processes and hence settling velocities of the suspended sediment. While flocculation processes are related to high spatial and temporal variability, a general approximation for the settling velocity of flocs (or single particles) as a function of the floc/particle diameter and its density is given by Stokes law (Rubey, 1933).

According to their size and synthesis, Eisma (1986) distinguishes between micro-flocs (<125 µm) and macro-flocs (<3-4 mm), built through collision of micro-flocs. The latter are much larger, but less dense and more fragile than micro-flocs (Eisma, 1986). The organic content, salinity, size of the single grains determine the flocculation ability, a measure of the probability of particles to aggregate when colliding (Eisma, 1986; Kranck, 1973), while high sediment concentrations and turbulent shear stress increase the probability of particle collision. Meanwhile, the turbulent shear stress controls the maximum floc size by breaking up large flocs in highly turbulent environments (Fig. 5) (van Leussen, 1994; Manning, 2004; Burban et al., 1989; Winterwerp, 1998; Winterwerp et al., 2006). The turbulent shear stress threshold, resulting in the maximum floc size and the highest settling velocities, is controlled by the prevailing environmental conditions, such as, for example, the sediment composition (Manning et al., 2010). It ranges from 0.3 N/m^2 to 0.6 N/m^2 (Manning, 2004; Winterwerp et al., 2006; Manning and Dyer, 2007; Manning et al., 2010), whereas for microflocs it tends to be higher (Fig. 5) (Manning, 2004; Manning and Dyer, 2007). Given that the suspended sediment concentration is below the critical value where hindering effects for sediment settling occur (Winterwerp, 2002), the settling velocity of a floc can be approximated by an exponential relationship with the suspended sediment concentration (Burt, 1986).

Bioaggregation, the flocculation process mediated by organic matter, is considered as the most important driver for flocculation in many coastal waters, including the Wadden Sea (Alldredge and Silver, 1988; van Straaten and Kuenen, 1957). It is mostly driven by the influence of microalgae, such as diatoms, binding mineral particles together, producing the so-called marine snow. High rates of bioaggregation or production of marine snow are observed during algae blooms with a corresponding increase in settling velocity of the suspended matter (Alldredge and Gotschalk, 1989). Another important trigger for bioaggregation is the presence of filter-feeding organisms, such as *Mytilus edulis* and *Cerastoderma edule* (van Straaten and Kuenen, 1957; Verwey, 1952) or *Hydrobia ulvae* (Andersen and Pejrup, 2002). Through biodepositon, these filter-feeders enhance sediment settling, while producing faecal pellets and pseudo-faeces (Graf and Rosenberg, 1997; Kautsky and Evans, 1987). Therefore, particle sizes and settling velocities increase in areas, where filter-feeding organisms are abundant (Andersen and Pejrup, 2002).

3 Flocculation processes on salt marshes

Flocculation processes are different on vegetated marsh platforms in comparison to unvegetated tidal flats (Graham and Manning, 2007). Due to a continuous decrease of flow velocity and turbulent energy towards the inner parts of the marsh, larger sediment particles and flocs are settling in the vicinity of the marsh edge and the tidal channels, while smaller sediment particles are transported further into the marsh (Fig. 2) (Christiansen et al., 2000; French and Spencer, 1993; Temmerman et al., 2004b; Temmerman et al., 2003a). A lower flow velocity and turbulent energy in the inner part facilitates sedimentation due to reduced vertical turbulent diffusion (Mudd et al., 2010; Neumeier and Amos, 2006; Shi et al., 1996), but may also inhibit flocculation of fine-grained sediments and reduce settling velocities, since the prevailing turbulent shear stress is usually lower than the critical turbulent shear stress for the maximum floc size (Fig. 2) (Neumeier and Amos, 2006; Fagherazzi et al., 2012). Furthermore, vertical flow gradients on vegetated salt marsh platforms (Leonard and Luther, 1995) affect sediment deposition on salt marshes (Neumeier and Amos, 2006). Flow velocity and turbulent shear stress within the vegetation canopy are considerably lower than above the vegetation or on the bare tidal flats, thereby promoting the settlement of cohesive sediment. On the other hand, increasing flow velocity and turbulent shear stress above the vegetation canopy inhibit sediment settlement through high flow velocities (Shi et al., 1996), while simultaneously increasing the floc sizes through high turbulent shear stress (if those are not exceeding the critical value) (Manning, 2004). During storm tides, such large flocs are travelling over the marsh and reach higher marsh elevations or slowly sink into the vegetation canopy. Thus, events of increased sediment settling may be observed there. Generally, flocculation processes on salt marshes are controlled by the density and the morphology of marsh vegetation (Graham and Manning, 2007) but are still unknown to a large extent.

4 Knowledge gaps in understanding of tidal basin sediment dynamics

Sediment dynamics on tidal flats are extremely complex and not fully understood yet. Attempts to assess them in a spatio-temporal context are rare and usually subject to high uncertainties (Widdows et al., 2004; Rahbani, 2011). In particular, the factors that determine the grain size distribution on the tidal flats are not sufficiently known. This leads to the inability to accurately estimate sediment resuspension and settling velocities (Wang et al., 2012). Furthermore, the actual processes of sediment resuspension and flocculation are still highly uncertain for sand-mud mixtures as well as the influence of biological parameters that show a strong spatial and temporal variability. For modelling the morphological development of salt marshes, these uncertainties pose a serious challenge, particularly because the long-term sediment availability, its short-term temporal variations, and the sediment composition are often unknown (Andersen et al., 2011).

V The sedimentary system of the Wadden Sea

1 The concept of a sand-sharing system

The morphological elements of the Wadden Sea system can be described as a sand-sharing system (Fig. 6), which distributes the sediment within the system according to prevailing hydrodynamics and morphological conditions (CPSL, 2001). Through redistribution of the sediment within the sand-sharing system, sediment required for the tidal flats to adapt to SLR is removed from the ebb-tidal deltas and transported into the tidal basins by tide or wind induced currents, and is therefore potentially available for deposition on the salt marshes (Elias et al., 2007; Hofstede, 1999a). Wind and wave activity significantly modify the sediment exchange between the ebb-tidal delta and the tidal basin by reducing the size of the ebb-tidal delta through erosion and an increased shoreward sediment flux into the tidal basin (Hofstede, 1999b; Walton and Adams, 1976). The incoming sediment is distributed through (sub-)tidal channels, from where adjacent tidal flats and salt marshes are inundated and supplied with allochthonous sediment.

2 Fine and coarse-grained sediment transport into the tidal basins

As a consequence of the shore-normal energy gradient (i.e. decreasing current velocities towards the inner tidal basin) and the so-called settling and scour lags (van Straaten and Kuenen, 1957; Postma, 1961), fine-grained sediments are transported further into the tidal basins, whereas the coarse-grained sediments tend to settle in the vicinity of tidal inlets (Flemming and Nyandwi, 1994). The settling and scour lags are resulting from the transport of the fine-grained sediment during its settling phase and the higher current velocity needed to resuspend a sediment particle from the seabed than to deposit it (van Straaten and Kuenen, 1957; Postma, 1961). These processes are considered as the most important ones for a net import of fine-grained sediments into the tidal basins of the Wadden Sea (van Straaten and Kuenen, 1958).

Additionally, the distortion of the tidal wave in coastal areas and the density-driven currents between the North Sea and the Wadden Sea as well as the (de-)stabilizing effect of physical sediment properties and benthic organisms are controlling the net amount of sediment accumulating within the tidal basins (CPSL, 2010). When travelling in shallow water or along an estuary or tidal basin, the distortion of the tidal wave induces shorter but stronger flood currents and longer but weaker ebb currents (Dronkers, 1986; van der Spek, 1997). Stronger flood currents (in comparison to the respective ebb currents) promote the import of coarse-grained sediment via bed-load and/or suspended transport (Dronkers, 1986; van der Spek, 1997; van Kreeke and Hibma, 2005; Wang et al., 2012). Meanwhile, an elongated high slack water period (in comparison to the previous and the following low slack water periods) may enhance the net import via suspended load transport and the sedimentation of fine-grained sediments (Dronkers, 1986; van Straaten and Kuenen, 1958; van Kreeke and Hibma, 2005). In enclosed, gently sloping tidal basins with most of the tidal flats located below MSL, the distortion of the tidal wave results in a larger import of fine-grained sediments compared to open-shaped, steeply sloping tidal basins with most of the tidal flats located above MSL (Dronkers, 1986; Pedersen and Bartholdy, 2006). The import of coarse-grained sediments is smaller or even negative in tidal basins with large tidal flat areas and larger in tidal basins with smaller tidal flat areas (Dronkers, 1986).

Due to these different drivers for the import of fine and coarse grained sediments, contrasting fluxes may occur within a tidal basin during a single tidal cycle (van Kreeke and Hibma, 2005). A net export of coarse-grained sediment in tidal basins with large tidal flat areas, for example, may be balanced or exceeded by the import of suspended fine-grained sediments (Ridderinkhof, 1997). Usually (during calm weather conditions), the suspended load import of fine-grained sediment dominates over the net import of coarse-grained sediments (Wang et al., 2012). During strong-wind and storm events, the import of coarse-grained sediments via suspended load transport considerably increases, thereby exceeding the import of fine-grained sediments (Santamarina Cuneo and Flemming, 2000; Van Goor et al., 2003). Seasonal variations of the total sediment import into the tidal basin of the Wadden Sea are induced by increased bioaggregation during spring and early summer algae blooms (Alldredge and Gotschalk, 1989) as well as through biodepositon of filter feeding organisms, which are more active during the warm summer months (Andersen and Pejrup, 2002). Density-driven currents, induced by higher variations of fresh water input into the tidal basins and larger seasonal temperature variations, may amplify the seasonal variations of the fine-grained sediment import, although its relevance for the Wadden Sea is under debate (van Beusekom et al., 2012; Wang et al., 2012).

3 Sediment sources

External sources of predominantly coarse-grained sediments other than the neighbouring tidal basins are found on the foreshore, the seaward beaches, and in the dunes of the barrier islands (CPSL, 2010). Most fine-grained sediments are supplied from riverine inputs such as the Rhine or the Elbe River as well as from soft-rock erosion on the English East Coast (Gayer et al., 2006) and presumably from ancient river valleys now located offshore (Dellwig et al., 2000). Other sources of fine-grained sediment are atmospheric deposition, primary production, direct fluvial input, and sediment from salt marsh erosion (Pedersen and Bartholdy, 2006; Pejrup et al., 1997). These sources strongly determine the availability of fine-grained sediments in the coastal North Sea and the import into the tidal basins of the Wadden Sea.

For most tidal basins in the Wadden Sea, sediment import from the coastal North Sea is the largest contribution to the total fine-grained sediment inventory (Dellwig et al., 2000). Pedersen and Bartholdy (2006), for example, found the import to vary between 52 to 82% in four Danish tidal basins. Estimated net imports of fine-grained sediment vary between 0.10 g m^{-3} (List tidal basin) to 0.53 g m^{-3} (Grådyb basin) for an average tidal cycle within a distance of only 60 km, for example (Pedersen and Bartholdy, 2006).

4 Trapping capacity of the tidal basins

An important parameter influencing the net sediment transport into the tidal basin is their trapping capacity. It is generally controlled by bed roughness and sediment stability, which are, to a large extent, determined by biological activity. Especially where vegetation canopies such as seagrass beds or salt marshes are present, but also where mussel beds and other reef-building epibenthic organisms are found, currents are slowed down, sediment resuspension is inhibited, and sediment accretion is enhanced. At the same time the sediment stability is increased due to the binding forces of the roots and the presence of biofilms inhibiting sediment resuspension (CPSL, 2010; Ward et al., 1984). Increased sediment stability additionally amplifies the scour lag effect and thereby contributes to the import of fine-grained sediments (Vos and van Kesteren, 2000).

5 Knowledge gaps in understanding the sedimentary system of the Wadden Sea

Looking into the future development of the salt marshes in the Wadden Sea, we identify the availability of fine-grained sediments and their settling velocities on salt marshes to be crucially important. These parameters largely depend on the amount and composition of sediments being imported into the tidal basins and their erodibility, once deposited on the tidal flats. Given the projected SLR for the Wadden Sea region, insufficient knowledge is available about how the tidal flats will evolve in the future with respect to their elevation and composition. One of the main reasons for this is the current practice of assessing the sediment budgets of the different tidal basins per sediment fraction, rather than looking at the combined cohesive and non-cohesive sediment budgets (Wang et al., 2012). Future modelling approaches will need to concentrate on the total sediment budget, thereby integrating the cohesive and non-cohesive sediments and their grain sizes. They additionally need to account for the morphological differences between the various tidal basins and their trapping efficiencies that are strongly controlled by the variable biological activity.

In this review, we studied the morphological processes within tidal basins consisting of channels, tidal flats and salt marshes (Fig. 6). However, it should be noted that in large tidal basins, subtidal flats comprise large areas (up to 60%). It is likely that the morphological behaviour in this deeper zone is not the same as described for the intertidal areas. Hardly any research has been performed on interactions between subtidal and intertidal flats on the sediment budgets of the tidal basins, but doing so could possibly further improve the understanding of the sedimentary system of the Wadden Sea.

VI An integrated conceptual model for the Wadden Sea salt marshes

By evaluating the available literature on hydromorphological processes directly and indirectly affecting the development of the Wadden Sea salt marshes, we identify important interactions between sedimentary processes taking place on salt marshes as well as on tidal flats and the entire tidal basins. Knowledge gaps are identified that we consider responsible for the limited ability of salt marsh models to predict the future development of the Wadden Sea salt marshes. Partly, the existence of these knowledge gaps is due to the lack of reliable empirical data, but also due to the high degree of complexity of the involved processes. However, for estimating the future development of coastal salt marshes under the influence of projected global sea level rise, these processes have to be accounted for in salt marsh modelling, since they drive the temporal and spatial variability of sediment supplied to the salt marshes.

In order to overcome this issue and bring forward the development of salt marsh models, we propose a conceptual model (Fig. 7) that integrates the most important interactions between the fringing salt marshes and the neighbouring tidal flats and tidal basins. This model aims to reduce the complexity of the system by identifying the processes that are directly responsible the quantity and quality of the sediment supplied to the salt marshes. It draws the sediment pathways that are relevant for the development of salt marshes and clarifies their role within the morphological system of the Wadden Sea.

1 Description of the conceptual model

Sediment import during calm weather periods is dominated by the import of fine-grained sediments via suspended sediment load and a minor contribution of coarse-grained sediment import via bed-load and/or suspended load transport (Fig. 7, 2). When onshore winds increase (inducing set-up of the water level), more coarse-grained sediments are imported via suspended sediment load, exceeding the import of fine-grained sediments during storm events (Fig. 7, 1). While flooding the tidal flats, parts of these suspended sediments are deposited on the tidal flats (Fig. 7, 5). The net sediment accumulation is mainly determined by the topography and the bed roughness of the tidal flats, which strongly depend on the physical sediment characteristics as well as the epibenthic structures on the tidal flats (Fig. 7, 3). Similarly, the physical sediment characteristics of the tidal flats and the biological activity on them determine the erodibility of the tidal flat sediments (Fig. 7, 3+4). The eroded sediment from the tidal flats and from the marsh scarp is either exported from the tidal basin via the tidal channels (Fig. 7, 5) or transported onto the salt marsh during strong wind or storm events (Fig. 7, 6). The composition of this sediment is rather fine, but depends on the characteristics of the tidal flat and the prevailing hydrodynamic conditions. Meanwhile, a direct input of sediment from the tidal channel towards the salt marsh is predominantly occurring during strong wind and storm events (Fig. 7, 7), whereas the composition of this sediment may be considerably coarser than the sediment that is eroded from the tidal flats. Once transported onto the salt marsh, a spatial pattern regarding the suspended sediment characteristics is observed (Fig. 7, 8+9). More and coarser sediments are found towards the seaward part of the marsh or in vicinity of the marsh creeks (Fig. 7, 8) compared to the inner part of the marsh, where less and finer sediments are found in suspension (Fig. 7, 9). The differences in suspended sediment characteristics induce higher settling velocities in the seaward part of the marsh, whereas these may vary vertically. Due to the higher turbulence level above the vegetation, flocculation is promoted, while the higher flow velocities allow the settlement of only the largest flocs/particles. In contrast, the floc size within the vegetation is smaller due to the lower turbulence level, but strongly reduced flow velocities allow the small particles and flocs to settle (Fig. 7, 8+9).

2 Suggested use of the proposed conceptual model

The proposed conceptual model has been developed in order to reduce the complexity of representing the involved processes in the (sub-)tidal sediment dynamics and thereby improve the estimation of boundary conditions and model parameters for salt marsh models. An implementation of this conceptual model includes the coupling of existing models that specifically address the different processes as shown in figure 7. Such a coupled modelling approach could be used to investigate how changes in the large-scale sedimentary system of the Wadden Sea would affect the development of the fringing salt marshes. Furthermore, the model could be used to estimate the influence of long-term (SLR) as well as short-term sea level variations (storm activity) on the future survival of the salt marshes. Besides the region of the Wadden Sea, the model could also be applied to comparable sedimentary systems, such as coastal lagoons with active inlets behind a coastal barrier.

Based on the proposed conceptual model, an integrated modelling approach could more efficiently capture the process interactions within the tidal basin - tidal flat - salt marsh continuum and thereby overcome some of the above identified knowledge gaps. For example, it could investigate and, to some extent quantify, the influence of a gradual increase of global and regional MSL in the coming century (Meehl et al., 2007; Vermeer and Rahmstorf, 2009; Wahl et al., 2010) on the sediment availability for coastal salt marshes as described in the following example:

A gradual SLR increases the demand for fine and/or coarse-grained sediments on the tidal flats and the demand for fine-grained sediments for the salt marshes to keep pace with SLR. The fine-grained sediment budget will be affected by a modified distortion of the tidal wave within the tidal basin. Accelerated sea level rise with tidal flats lagging behind in net accretion would increase the proportion of shallow subtidal areas at the expanses of intertidal flats. A modified tidal wave distortion could favour the import of fine-grained sediments during calm weather conditions, increasing, in turn, the sediment availability for the fringing salt marshes. The single-grain settling velocities might decrease and the flocculation ability of the sediment particles might increase correspondingly.

In contrast, increasing storm surge heights and a possible moderate increase of storm activity (Weisse et al., 2006; Weisse et al., 2012; Woth et al., 2006), could lead to a stronger net export of fine-grained sediments. In the long-term, this could amplify the trend towards coarser sediments in the Wadden Sea and decrease the sediment availability for salt marshes. With a coarser sediment fraction available, the single-grain settling velocities would increase and the flocculation ability of the sediment would decrease.

VII Conclusions

The above conceptual model is proposed as a framework for salt marsh modellers in order to facilitate the integration of important interactions between processes taking place within tidal basins, tidal flats, and on salt marshes for estimating future salt marsh development. It graphically displays the following more generic conclusions that we draw from this study:

1) Sediment availability for salt marshes depends on the morphology of tidal basins and on whether future SLR will be accompanied by increasing storm activity or not.

2) Changing grain-size distribution in response to climate change potentially affects the salt marsh development by modified sediment availability and changes particle/floc settling velocities.

3) Flocculation processes on salt marshes are strongly influenced by the available sediment and its grain-size distribution as well as the structural dynamics of salt marsh vegetation and may considerably influence the spatial accretion patterns and the vertical accretion rates.

Existing salt marsh models are well capable of identifying important processes dominating salt marsh accretion. However, important processes in the tidal basins and on its tidal flats that determine the local sediment availability and sediment characteristics are not yet sufficiently incorporated.

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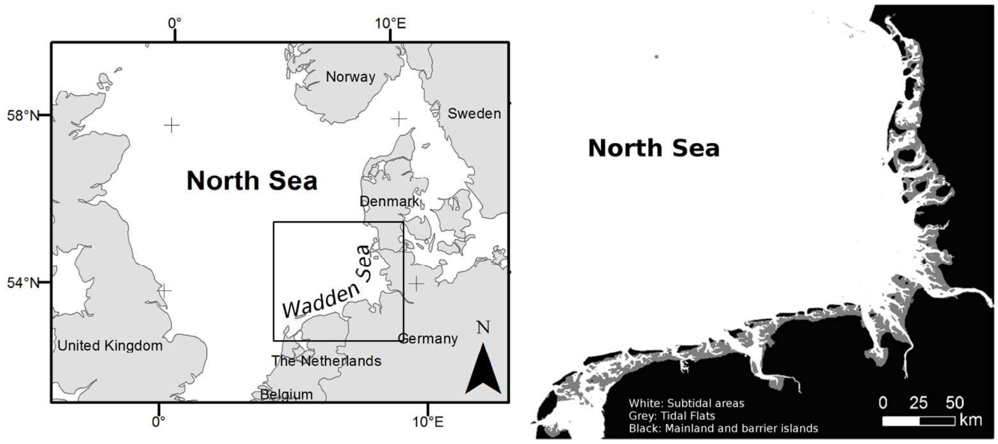

Figure 1: Location of the Wadden Sea along the south-eastern coast of the North Sea (left). The Wadden Sea area consists of the subtidal areas (white), the tidal flats (grey) and the barrier islands and mainland coasts (black) (right).
160x70mm (300 x 300 DPI)

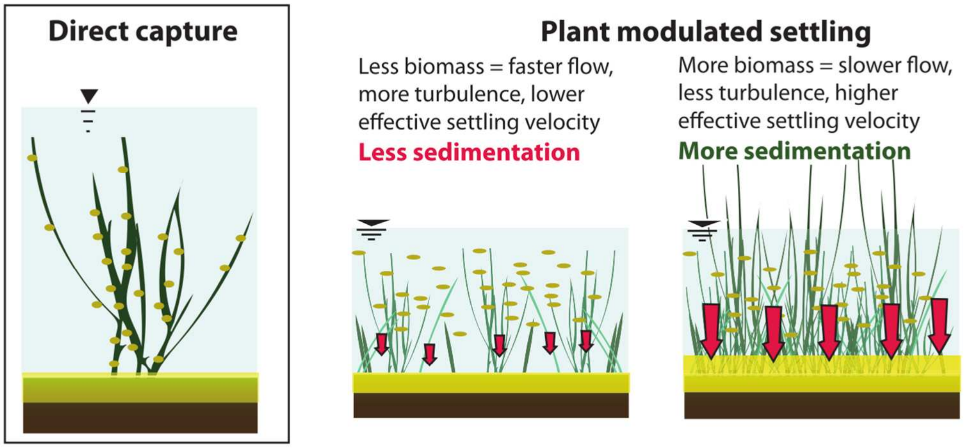

Figure 2: Vegetation effects leading to enhanced allochthonous marsh accretion. Source: Fagherazzi et al., 2012.
120x57mm (300 x 300 DPI)

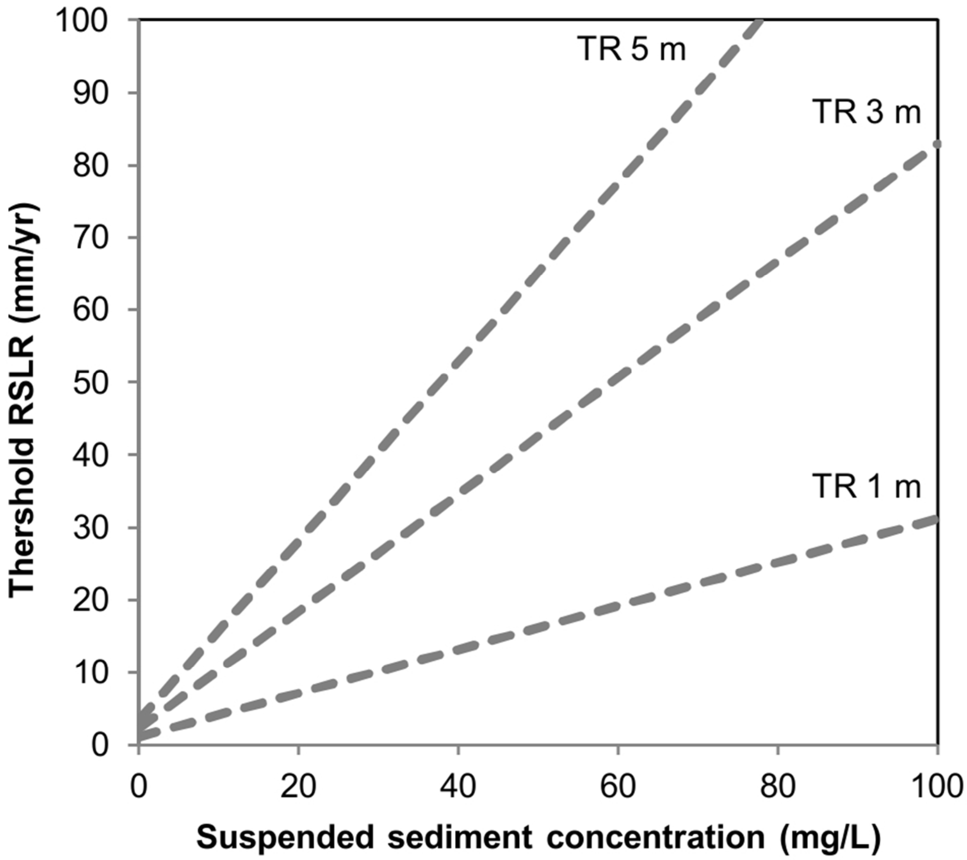

Figure 3: Threshold relative SLR rates for the survival of salt marshes as a function of tidal range (TR) and local sediment availability (suspended sediment concentration), modelled with five different salt marsh models. Dashed lines indicate three different tidal regimes (1 m, 3 m, and 5 m). Source: Modified after Kirwan et al., 2010.
83x73mm (300 x 300 DPI)

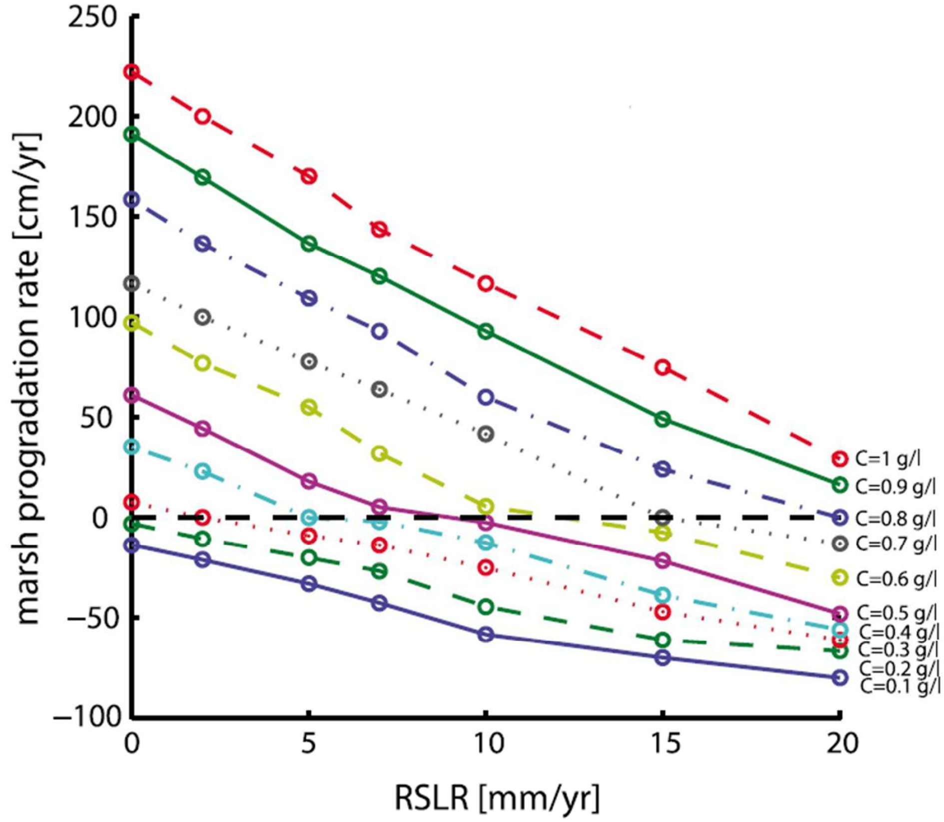

Figure 4: Lateral marsh dynamics in response to RSLR and sediment availability (C). Source: Mariotti and Fagherazzi, 2010.
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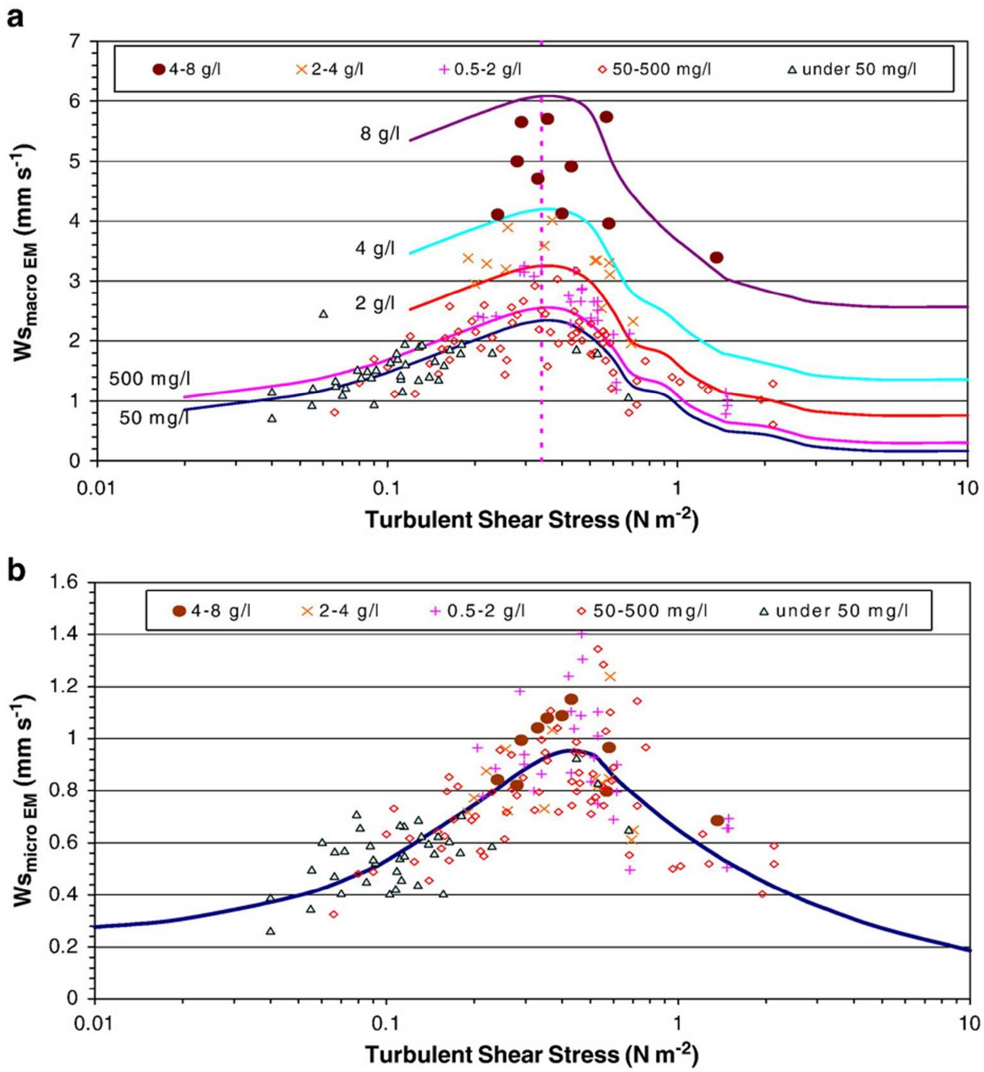


Figure 5: Floc settling velocity (w_s) as a function of turbulent shear stress and suspended sediment concentrations for macro-flocs (a) and micro-flocs (b) assessed for several European estuaries. Source: Manning and Dyer, 2007.
160x174mm (300 x 300 DPI)

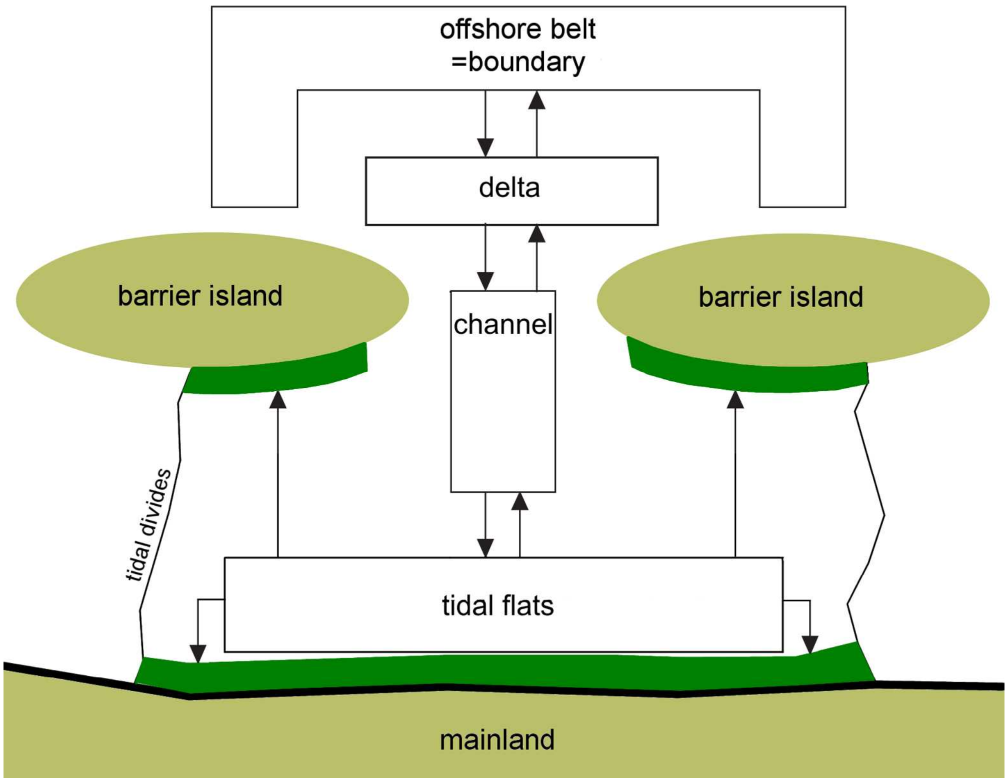
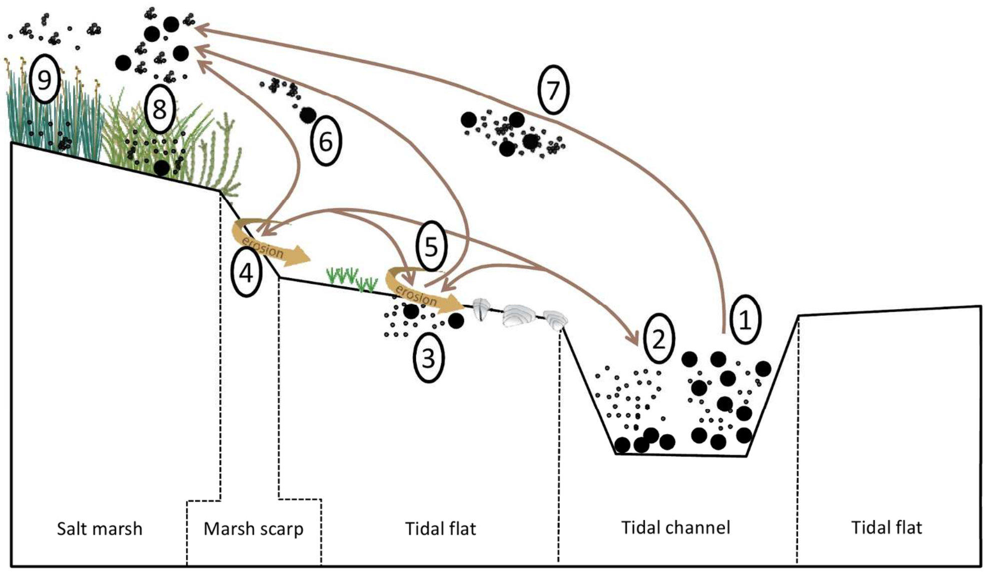


Figure 6 (modified after Kragtwijk et al., 2004): Morphological elements of the sand-sharing system for one tidal basin, as schematized by the "Aggregate scale morphodynamic model of integrated coastal systems" (ASMITA) model. The fringing salt marshes are added as an additional morphological element that act as a sediment sink for the tidal basin. Source: Modified after Kragtwijk et al., 2004.
160x129mm (300 x 300 DPI)



1) Sediment influx through tidal channel during storm events (coarser sediment)
2) Sediment influx through tidal channel during calm periods (finer sediment)
3) Sediment resuspension on tidal flats affected by physical (e.g. grain size) and biological (benthic flora and fauna) sediment properties.
4) Sediment resuspension at marsh edge (controlled by physical and biological parameters as well as the slope and height of the scarp)
5) Sediment exchange between tidal channel, tidal flat, and salt marsh
6) Transport of sediments resuspended from the tidal flats and the marsh edge towards the salt marsh
7) Direct sediment transport from tidal inlet to salt marsh during storm events
8) Marsh accretion in seaward part of the marsh (more and coarser sediment)
9) Marsh accretion in landward part of the marsh (less and finer sediment)

Figure 7: Conceptual model of sediment dynamics between the different morphological units in the Wadden Sea (tidal channel, tidal flats, salt marshes; subtidal flats have been omitted because of gap in knowledge).
160x134mm (300 x 300 DPI)